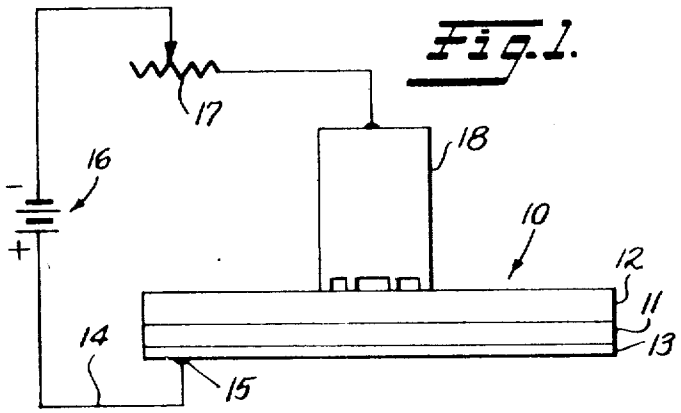
March 7, 1972 W. W. LESTER 3,647,665

ELECTROCHEMICAL DEVICE FOR PRODUCING A RECORD

Filed July 30, 1969 2 Sheets-Sheet 1

Fig. 1.



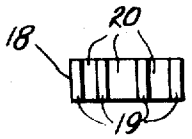
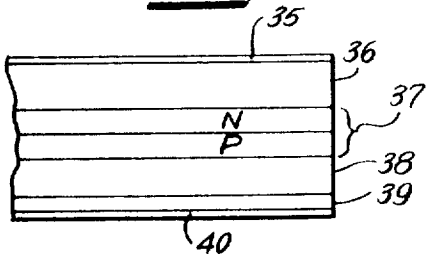


Fig. 2.

Fig. 5.



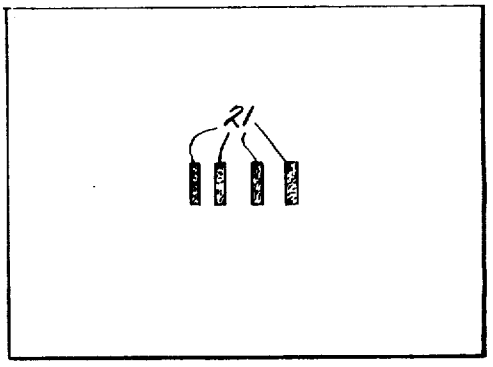
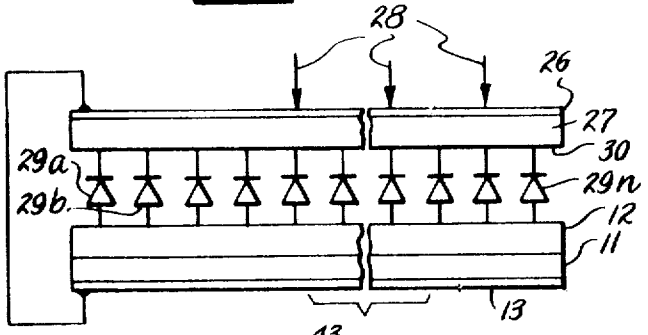


Fig. 4.

Fig. 3.



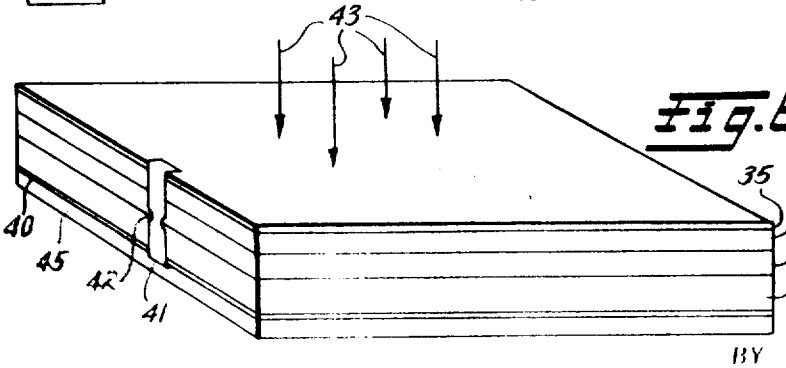


Fig. 6.

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ELECTROCHEMICAL DEVICE FOR PRODUCING A RECORD

Filed July 30, 1969 2 Sheets-Sheet 2

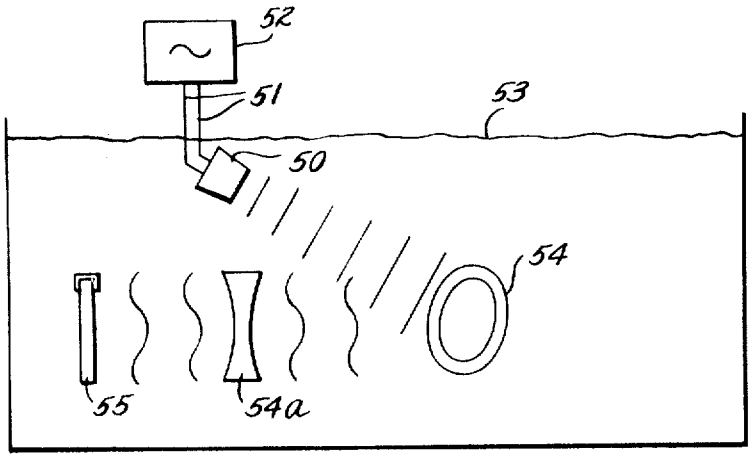


Fig. 1a.

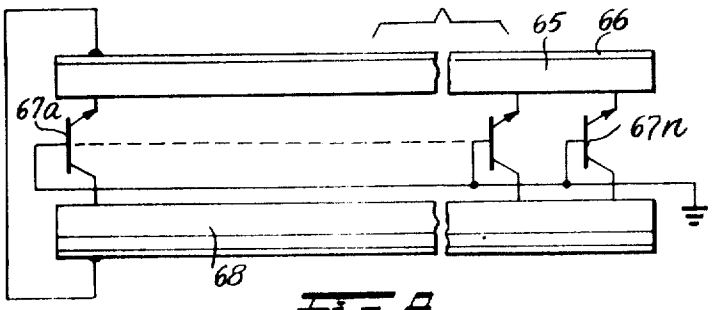


Fig. 8.

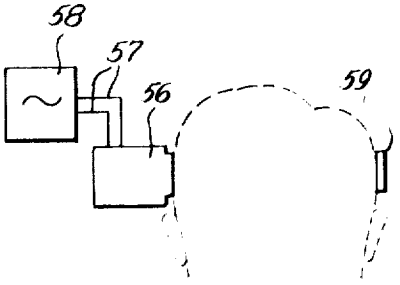


Fig. 7b.

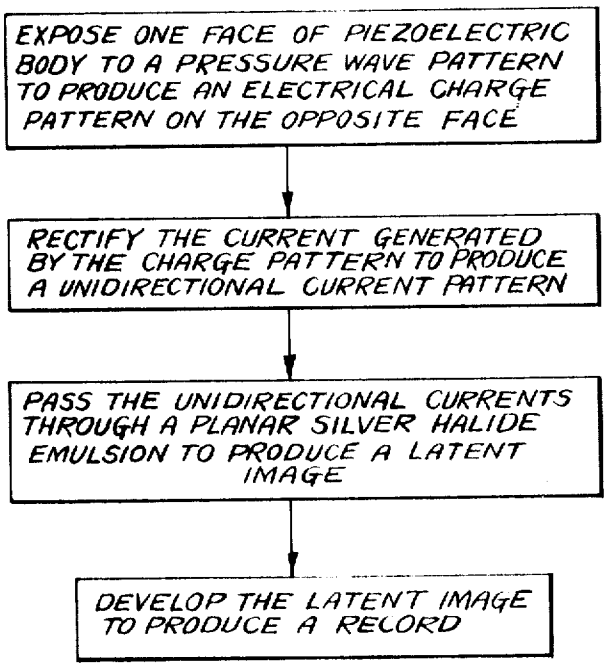


Fig. 10.

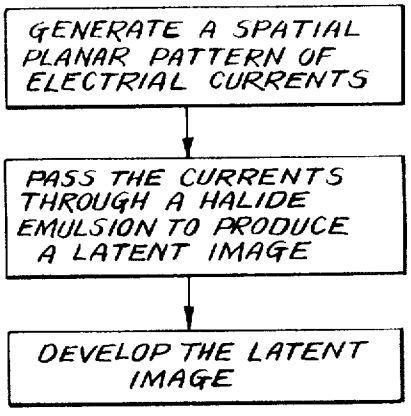


Fig. 9.

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ELECTROCHEMICAL DEVICE FOR PRODUCING A RECORD

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Int. Cl. B01k 3/00; H01v 7/00

U.S. Cl. 204—194 7 Claims

ABSTRACT OF THE DISCLOSURE

An apparatus for producing a record in the nature of a photograph wherein small electrical currents are caused to pass through a silver halide emulsion of the type normally used in photographic printing paper. The invention is especially useful in producing a record of a pressure pattern such as an ultrasonic pattern in a fluid medium wherein one surface of a piezoelectric transducer is exposed to the pressure pattern, that surface being coated with a thin layer of an electrically conductive material. A planar array of semiconductor diodes is placed in a parallel contacting relationship with the other surface of the piezoelectric transducer to rectify the charge pattern resulting from stress in the transducer due to the pressures applied thereto. The rectified signals on the output side of the diode array are applied to a major face of a moistened layer of silver halide emulsion of a type normally used in photographic printing papers or films. The back of the emulsion sheet is coated with, or is in contact with, an electrically conductive sheet which is electrically connected to the conductive layer on the piezoelectric transducer. After exposure of the emulsion layer to currents generated by the piezoelectric crystal the emulsion is removed and processed in a conventional manner to develop the latent image produced therein by the electrical currents and thereby produce a record of the pressure patterns applied to the piezoelectric transducer. In the use of the apparatus described herein and in the method of producing the record, the emulsion is shielded from light of a kind which would produce an image.

This invention relates to apparatus for producing a record in the nature of a photograph and is especially useful in the production of a record of pressure patterns resulting from ultrasonic wave energy.

In the general field of ultrasonic imaging many devices have been invented which are capable of, broadly speaking, responding to pressure waves in a fluid medium, converting those waves to electrical signals, and displaying the information contained in the electrical signals in a manner which is representative of the distribution of the pressure pattern. The prior art devices have generally involved the use of an evacuated chamber having a pressure responsive wall exposed to the pressure pattern with means to transduce the pressure information into electrical form and to transfer the information in electrical form to some remote point. The display has generally been in the form of a cathode ray tube, although devices have been produced for producing a written record through printout tubes or the like.

In any event, the necessity for an evacuated chamber has imposed severe limitations on the utility of such devices. For example, it is undesirable to have an evacuated envelope with the accompanying vacuum pumps and the like in an apparatus which weighs several pounds in a surgical theater where such device might be desirable for

ultrasonically imaging the interior of a brain to locate a tumorous growth. Similarly, such evacuated chambers are limited as to the depth in water at which they can be used because of the pressure and the resulting structural problems.

In addition, the prior art devices have not been inherently capable of producing a record of the pressure patterns in a simple and straightforward manner.

An object of the present invention is to provide an apparatus which produces a record in the nature of a photograph of a pressure pattern.

Another object is to provide means for producing a written record of a pattern of electrical currents.

A further object is to provide a solid state ultrasonic imaging device.

Another object is to provide an ultrasonic imaging apparatus which is vastly simpler and less expensive than prior art devices.

Yet another object is to provide a method of producing a permanent record of a pattern of electrical currents by imposing the current pattern on a chemical medium to produce a latent image and then developing the latent image.

In order that the manner in which the foregoing and other objects are obtained in accordance with the invention can be understood in detail, particularly advantageous embodiments thereof will be described with reference to the accompanying drawings, which form a part of this specification, and wherein:

FIG. 1 is a schematic representation of an apparatus for producing a latent image in accordance with a current pattern;

FIG. 2 is a plan view of the face of an image die used in the apparatus of FIG. 1;

FIG. 3 is a drawing of a record produced by the apparatus of FIG. 1;

FIG. 4 is a schematic representation of an apparatus for producing a latent image of a pressure pattern;

FIG. 5 is a detailed enlargement of a portion of an apparatus usable for producing a pressure pattern image;

FIG. 6 is a perspective view of one embodiment of an apparatus in accordance with the invention;

FIGS. 7*a* and 7*b* are diagrams showing examples of applications of the apparatus of FIG. 6;

FIG. 8 is a schematic representation of a second embodiment of the invention;

FIG. 9 is a flow diagram illustrating one method of the invention;

FIG. 10 is a flow diagram of a second method of the invention.

FIGS. 1, 2 and 3 will be used jointly to discuss a basic principal which is fundamental to the operation of the invention. FIG. 1 shows a rectangular piece of printing paper which will be referred to as a photoelement indicated generally at **10**, the paper constituting a conventional fibrous paper backing sheet **11** with a coating of a halide emulsion **12** such as silver chloride or other noble metal halide on one surface thereof. FIG. 1 is, of course, schematic and is not intended to represent relative dimensions of the emulsion coating or paper backing. The term "photoelement" as used herein refers to photoresponsive elements of the type commonly used as photographic printing papers and includes silver halide emulsions, other emulsions of metallic salts in which an image can be formed, evaporative film types of papers and any of the wide variety of chemical compositions which are usable for this purpose.

The emulsions or evaporative films can be coated on a wide variety of supports in accordance with usual practice including paper. It should be noted, however, that the class of supports usable does not include cellulose nitrate or acetate film, glass or other substances which are good electrical insulators. This eliminates the majority of materials used as "films" to produce a negative image because such films are generally produced with an electrically nonconductive support. However, it must be recognized that the nonconductivity of the support is the only reason for not including this class of articles and that the term "photoelement" is intended to include any having conductive supports.

A layer of electrically conductive material **13** is placed in parallel, continuously contacting relationship with the back of the sheet **11** for the purpose of providing a conductive electrode with which to complete a circuit through the paper. The layer **13** can be any conductive metal, such as stainless steel or the like, and can be either rigid or flexible depending upon the use to which the structure is put. An electrical conductor **14** is soldered or otherwise fastened in good electrically conductive relationship at **15** to plate **13**, and is also connected to the positive terminal of a DC voltage supply illustrated in FIG. 1 as a battery **16**. The negative terminal of battery **16** can be connected to one terminal of a variable resistor **17**, the other terminal of which is electrically connected to a die **18** which is used to produce the image. The variable resistor **17** is an optional element which is included in the circuit to illustrate the fact that current can be controlled at the low levels involved to produce the image in varying periods of time and of various optical densities.

Die **18** is illustrated in FIG. 1 as being a rectangular block of a metallic material which is a good electrical conductor and which has a pattern on one face. That face is placed in contact with the emulsion layer of the printing paper. For purposes of this discussion, a very simple pattern comprising four parallel rectangles has been selected for the face of die **18**. Thus pattern is shown in FIG. 2 wherein rectangular faces **19** protrude from the remainder of the die and lie in a common plane. Portions **20** are recessed from faces **19**.

With the apparatus shown in FIG. 1 a latent image can be produced in the emulsion layer **12** of printing paper **10** by first moistening the paper to render it electrically conductive and by then connecting it to the electrical supply as shown with the die in firm contact with the emulsion layer. When electrical currents on the order of milliamperes are passed through the circuit including the die, the emulsion, the paper and the backing plate **13**, a latent image is produced in the emulsion. The die is then removed, the paper and emulsion is separated from the backing plate, and the printing paper is developed in the same manner as if it had been exposed to light. The resulting image appears like that shown in FIG. 3 wherein the dark rectangules **21** are the same size and shape as the flat faces **19** on die **18**.

The electrical conductivity of the fluid used to moisten the paper affects the resistance of the system and can be selected to match the impedance of other portions of the system as necessary. Solution of salts in water can be used in any concentration desirable. Also, a standard developer solution, such as FR paper developer, diluted 1 part to 3 parts water by volume, has been found to be usable.

It must be emphasized that the entire process discussed above takes place in the absence of light. Ideally, no electromagnetic radiation of any form is present during this process, although it will be recognized by those skilled in the art that certain frequencies of red, yellow and infrared radiation have no effect on certain types of printing paper and that those forms of light can be present without deleterious effect. The major point, however, is that there is no light needed to produce the images shown in FIG. 3. The images are produced totally by the passage of current through the emulsion between die **18** and backing plate **13** by connection of the battery and electrical conductors to these elements to complete a circuit. Obviously, any form of voltage source can be used, but it has been observed that only current flow resulting from the imposition of a negative voltage at the emulsion produces the desired image. Thus, if an alternating supply is used it is desirable to rectify the alternating signal into a unidirectional signal before applying it to the emulsion.

An example of the method of producing an image in accordance with the invention follows: A die bearing the image of printer's type on one face, the type having a total cross-sectional area of 0.15 square inch was pressed in contact with the emulsion side of a piece of photographic paper manufactured by Agfa-Gevaert and identified as Brovira BS–1 Contrast 3, emulsion number 223334–34, special extra white glossy single weight paper. The paper was pre-soaked for 30 seconds in a solution of developer fluid identified as FR paper developer, diluted 1 part to 3 parts water by volume in accordance with the instructions provided with the developer. A DC power supply was connected to the printer's die and to a stainless steel plate placed under the paper. The printer's type die was given a negative polarity. A current of 225 milliamperes was applied for 10 seconds with a voltage of 2 volts. The total charge density was approximately 16 coulombs per square inch averaged over the face of the type. The paper was subsequently developed for 2 minutes in the manner normally used for printing paper of this type after exposure to light, and was thereafter stopped, fixed, washed and dried. The above process produced a clear black image of the letters on the face of the printer's die.

The printer's type used in the above operation is a standard metal alloy including lead, antimony and tin. Various other metals have been experimented with, including a coin which is a nickel-copper alloy; a length of electrician's solder having a tin-lead alloy; and a tinned copper wire having a tin-lead alloy coating.

Images can be produced by various magnitudes of current and for various periods of time. Preferably, the voltage applied should be greater than zero but less than 10 volts. This is not an absolute upper limit, but produces a good image with minimal deleterious side effects. A more meaningful measure of the current required to produce a suitable image is the charge density, which is a product of the current passed through the emulsion and the time for which the current is allowed to flow, per unit area. Preferably, the charge density lies in the range of about 1 to 200 coulombs per square inch.

It is also possible to produce a direct image rather than a latent image. The production of a direct image in photographic paper is well known and is used by commercial photographers. In the production of a direct image in accordance with the invention, a greater current-time product, or charge density, is used than would be used in producing a latent image. The resulting image then appears on the paper directly without developing. The paper can subsequently be stopped, fixed and washed to render the image permanent.

An application of this principle to an imaging apparatus is shown in FIG. 4 wherein a laminated structure comprising an emulsion layer **12**, a paper backing **11** and an electrically conductive backing sheet **13** are placed in a parallel contacting relationship as in FIG. 1. An electrical conductor **25** connects the backing plate **13** to a thin electrically conductive metallic layer **26** which is formed on or adhered to one major face of a piezoelectric transducer **27**. Transducer **27** is a relatively thin slab or sheet of piezoelectric material such as, for example, lead zirconate titanate (PZT), the thickness of which is determined by the frequency to which it is intended to respond. As is well known in the art, when a piezoelectric crystal is physically stressed, it produces an electrical

signal in the form of charges. The application of pressure at various points on one major face, represented in FIG. 4 by arrows **28**, produces a pattern of charges on the opposite major face **30**. It will be apparent that electrically conductive layer **26** can be thin and flexible so as to transfer the pressure pattern applied thereto to the upper major face of transducer **27**, allowing it to respond to the pressure pattern and to produce charges on the lower major face. Alternatively, the layer **26** can be made an odd multiple of half wavelengths thick at the operating frequency to transfer the pressure pattern to the transducer face.

The pressure pattern which is to be applied when the device is used as an ultrasonic imaging apparatus is an alternating pressure patern, i.e., the stresses applied alternate with time in one direction and the other, because of the nature of the stimulating signal which produces the ultrasonic energy. Thus, the charges produced on face **30** of transducer **27** will be charges of alternating polarity. As discussed above, it is desirable to provide charges of a single polarity to the emulsion. Thus, a plurality of semiconductor diodes **29***a*, **29***b* . . . **29***n* are connected between various points of face **30** of transducer **27** and spatially related points of the upper surface of emulsion **12**. These diodes which are shown as discrete circuit elements in FIG. 4 provide the necessary half-wave rectification so that a unidirectional current can flow from face **30** of transducer **27** to the emulsion.

It will be recognized that piezoelectric material such as PZT is not usually regarded as a conductor of electricity. It can, of course, be manufactured with fine particles of electrically conductive material suspended or dispersed therein so that it is conductive or semiconductive, or, by other means known to the art, made with low resistivity. However, this technique is not necessary so long as the impinging pressure signal is an alternating signal which generates AC charge and current patterns. The crystal acts as a generator of AC and accordingly provides a path for the completion of the circuit.

It will be recognized that the connection of individual diodes in the manner indicated in FIG. 4 is not a practical solution to the rectification problem because it is simply not possible to attain a diode density adequate to give acceptable resolution in the final image. Thus, an array of diodes formed in the manner of an integrated circuit is used in a practical working model of the apparatus, this being illustrated in FIG. 5. FIG. 5 shows a small section of a completed imaging apparatus comprising a thin flexible metallic layer **35** which can be exposed to a fluid medium wherein pressure waves are to be generated. Layer **35**, which can be a thin sheet, coating, or block having a thickness equal to an odd number of quarter wavelengths, is formed on, as by deposition, or adhered to one major face of a piezoelectric transducer **36**. The other major face of transducer **36** is placed parallel to and in contact with one surface of an array of semiconductor diodes indicated at **37**, the diodes including an N layer and P layer. The two layers are each separated into a grid array of individual elements in the formation process. Arrays of such diodes having extremely high diode per square centimeter density are now commercially available. A discussion of the manner in which diode arrays are produced is descirbed in the Apr. 28, 1969, issue of Electronics at pages 159 and 160. Another discussion of a technique for producing diode arrays appears in the Bell System Technical Journal, vol. 47, No. 9, pages 1827–1854. These articles discuss making photodiode arrays, but the technique for making arrays of diodes which are not photosensitive is very similar.

Beneath the diode layer is the emulsion layer **38** of the printing paper with a paper backing **39** and an electrically conductive layer **40**. Layer **40** can convenienty be made in the form of a foil or simliar thin sheet so that the emulsion, paper and metallic backing can be removed, or "stripped" as a unit, from the diode layer for developing.

FIG. 6 shows a perspective view of a complete assembly usable for ultrasonic imaging. In FIG. 6 the various layers are numbered as in FIG. 5 except that no individual paper backing is shown for the emulsion. It will be recognized that the emulsion can be produced with an electrically conductive backing, thus eliminating the need for the paper, or that it can be produced in the form of a solidified gelatin sheet which is accompanied by no specific backing. Electrically conductive layers **35** and **40** are connected by a strap **41** of electrically conductive material to complete the circuit. Strap **41** has a narrow portion **42** which allows it to be severed when the emulsion is removed for developing. The application of pressure waves to layer **36** is indicated by arrows **43**. A structure of the type shown in FIG. 6 can be made in any desirable size, limited only by the manufacturing techniques for producing the necessary diode array and the transducer portion. However, should the desired size exceed available segments, several complete units can obviously be used in edge-to-edge relationship.

The voltages produced by the transducer depend upon the materials used for the transducer itself, i.e., whether the material is quartz, lead zirconate titanate, or the like, and what other impurities or percentages of the materials might be used. These variables can affect the impedance of the transducer and, accordingly, the voltages produced by various pressure levels of the force which stresses the transducer. In the following table, several pressures are given at several operating frequencies and thicknesses of transducers for the production of approximately 30 millivolts which is regarded as the minimum voltage to produce an image in a system which includes transducers, diodes and the emulsion layer. These are threshold acoustic peak pressures using a typical commercial PZT transducer.

Threshold acoustic peak pressure required for operation	Operating frequency, mHz.	Thickness (equal to expected resolution
0.1 atm.	20.0	4 mils=0.1 mm.
.05 atm.	10.0	8 mils=0.2 mm.
.03 atm.	5	16 mils=0.4 mm.
.01 atm.	2.0	40 mils=1.0 mm.
.0099 atm.=900 dynes/cm.^{2}	0.15	13.3 mm.≈½ inch.

An additional layer can be attached to a transducer of the type shown in FIG. 6 when the transducer is intended to be immersed in a body of fluid in conjunction with a generator for producing ultrasonic waves in the fluid. In such circumstances, the ultrasonic waves are dispersed throughout the fluid and cannot readily be confined to the front, or transducer portion, of the image producing device. It is therefore desirable to laminate a sound absorber such as a sheet of soft rubber onto the back of the transducer, i.e., parallel with and in continuous contacting relationship with back plate **40**. This is shown in FIG. 6 as a layer **45**. The thickness of this layer depends upon the acoustic power levels to be used.

FIGS. 7*a* and 7*b* show examples of two applications of the subject device utilizing the advantageous characteristics it possesses. In FIG. 7*a* a transducer head **50** capable of producing ultrasonic energy is energized by a signal carried by conductors **51** from an ultrasonic oscillator **52**. The energy is propagated in a fluid medium **53** in the direction of an object **54** an image of which is to be produced. Energy is reflected from object **54** and passed through a focusing device **54***a* to the imaging device indicated generally at **55**. The imaging device **55** can be constructed as shown in FIG. 6, and supported in the fluid medium in any convenient manner. After the exposure of device **55** to ultrasonic energy reflected from the object **54**, the imaging device is removed to a dark environment where the emulsion is stripped and developed to produce a permanent record in the nature of a photograph, although produced without light, of the object **54**.

FIG. 7*b* shows one arrangement for examining the interior of the brain of a patient, primarily for the purpose of determining the existence and exact location of tumorous growths or other anomalies within the brain. A transducer **56** is energized by a signal carried through conductors **57** from an ultrasonic oscillator **58**, the energy being coupled from the transducer into the patient's head. The energy passes through the skull and brain of the patient and stimulates the transducer portion of imaging apparatus **59** which is acoustically coupled to the opposite side of the patient's head. Device **59** can be constructed as shown in FIG. 6. Unique transmission properties of tumorous growths and the like will then produce a latent image in the emulsion of device **59** which can be stripped and developed as previously discussed.

A further embodiment of an ultrasonic imaging device using the basic principles discussed above but with the addition of signal amplification means is shown in FIG. 8. A piezoelectric transducer **65** has a metallic electroconductive layer **66** adhered to one face thereof, this face being exposed to wave energy. The back surface of transducer **65**, on which a pattern of electrical charges appears in response to stress patterns, is connected to the emitter electrodes of a plurality of transistors **67***a–n*, the collector electrodes of which are connected to points on an emulsion **68**. The base electrodes of transistors **67***a–n* are connected to a common biasing source to allow the transistors to perform an amplification function and rectify. The emulsion is laminated to suitable backing and conductive layers as before. It should be understood that the apparatus of FIG. 8 is to be regarded in the same light as that of FIG. 4, being merely a schematic representation of a suitable device. The transistors can be produced in the form of a semiconductor array in a manner similar to the diode array described with reference to FIG. 5.

FIGS. 9 and 10 show flow diagrams of the method steps of two methods involved in the present invention. FIG. 9 shows the method of producing a latent image in a halide emulsion by first generating a spatial planar pattern of electrical currents, passing the currents through a halide emulsion to produce a latent image and then developing the latent image to produce a permanent record.

FIG. 10 shows the method of producing a record of an ultrasonic or other wave pattern which comprises the steps of exposing one face of a piezoelectric body to a pressure wave pattern to produce an electrical charge pattern on the opposite face, rectifying the current generated by the charge pattern to produce a unidirectional current pattern, passing the unidirectional current pattern through a planar silver halide emulsion to produce a latent image and developing the latent image to produce a record in the nature of a photographic record without exposure to light.

While certain advantageous embodiments have been chosen to illustrate the invention, it will be understood by those skilled in the art that various changes and modifications can be made therein without departing from the scope of the invention.

What is claimed is:

1. An apparatus for producing an image in the absence of light comprising the combination of

a planar photoelement capable of conducting electrical current;

means comprising a piezoelectric transducer for producing a pattern of electrical potentials and for imposing said pattern on one surface of said element; and

means for completing an electrical circuit from another surface of said element to said pattern producing means to cause current flow through said element.

2. An ultrasonic imaging device comprising the combination of

transducer means having a surface exposable to a pressure pattern for producing, on a second surface, an electrical pattern spatially related to said pressure pattern;

semiconductor means having a first surface in contact with said second surface of said transducer means, and a second surface,

for producing at said second surface an electrical pattern related to the electrical pattern produced on said first surface of said semiconductor means; and

image producing means in contact with said second surface of said semiconductor body for producing a permanent image spatially related to, and in response to, said electrical pattern.

3. Apparatus according to claim **1** wherein said image producing means comprises

a planar photoelement capable of conducting electrical current; and

means for completing an electrical circuit to said exposable surface of said transducer means.

4. An ultrasonic imaging apparatus comprising the combination of

a thin sheet of piezoelectric material having two major faces,

a first body of electrically conductive material on one of said major faces;

a thin sheet of semiconductor rectifying material having two major faces,

one of said major faces of said sheet of rectifying material being parallel to and in continuous contact with the other major face of said sheet of piezoelectric material;

a sheet of image producing material having a major face in contact with the other major face of said sheet of rectifying material;

a second body of electrically conductive material on the other major face of said sheet of image producing material; and

circuit means interconnecting said first and second electrically conductive bodies.

5. An apparatus according to claim **4** wherein said rectifying material is poled to conduct electron current toward said sheet of image producing material.

6. An apparatus according to claim **4** wherein said first electrically conductive body is a thin metallic coating.

7. An apparatus for producing a record of an ultrasonic image comprising the combination of

a thin sheet of piezoelectric material;

a metal electrically conductive body on one major surface of said sheet of piezoelectric material to form a reference potential plane, said body being exposable to an ultrasonically produced pressure pattern;

a semiconductor body having two major surfaces and having a thickness dimension significantly smaller than the dimensions of said major surface,

said semiconductor body including two semiconductor types,

said semiconductor body being characterized by the property of rectification in the direction of its thickness dimension,

one major surface of said semiconductor body being parallel to and in electrically conductive relationship with the other major surface of said sheet of piezoelectric material;

a thin sheet of photosensitive material parallel to and having one major surface in electrically conductive relationship with the other major surface of said semiconductor body;

a body of electrically conductive material on the other major surface of said sheet of photosensitive material; and

circuit means interconnecting said bodies on said photosensitive material and said piezoelectric material.

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JOHN H. MACK, Primary Examiner

R. L. ANDREWS, Assistant Examiner

U.S. Cl. X.R.

204—2; 310—8